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DEDICATED COMPACT FLUORESCENT FIXTURES: THE NEXT GENERATION FOR RESIDENTIAL LIGHTING

ABSTRACT

This paper presents a rationale for seeking increased use of dedicated pin-base fixtures for compact fluorescent lamps in residential applications and outlines the need for a national strategy to accelerate their adoption. About three billion light fixtures illuminate America’s 96 million homes. Each year, 500+ domestic and foreign manufacturers collectively sell about 165 million residential fixtures with a retail value of over four billion dollars, half of which are imported. Approximately 60% of U.S. residential fixture sales are hardwired and 40% are portable. In terms of energy use and market sales, ceiling-mounted fixtures and table lamps emerge as among the most significant segments of the market. A fundamental market barrier for compact fluorescent lamps (CFLs) is that screw-base systems often perform extremely poorly once installed within fixtures. Our measurements show up to a 75% loss in nominal CFL light output when the sub-optimal thermal and optical environment within fixtures is accounted for. We also find that the ideal CFL lamp type varies as a function of fixture type. With hardwired, dedicated CFL fixtures the lighting designer has the opportunity to develop a marriage between fixture and source leading to appropriate aesthetic and photometric integration, necessary functions if CFLs are to have a lasting place in the residential market place. Dedicated fixtures designed for optimal thermal and optical operation of CFLs also offer a solution least likely to allow a “snap back” to less efficient incandescent sources.

INTRODUCTION

Recent federal initiatives, including the Bush Administration’s Energy Policy Act of 1992 and the Clinton Administration’s Climate Change Action Plan, call for a renewed national commitment to energy savings. These actions reflect the realization that efforts to save energy during the two decades since the term “energy crisis” became a household word have not delivered their full potential. Although most end-use areas have seen 30% to 50% efficiency improvements, there remain numerous efficiency resources that have not been exploited. Moreover, energy efficiency has at times been implemented in a somewhat clumsy manner—one which is not well received by consumers.

Residential lighting presents a microcosm of these larger trends. Each year the energy used to light U.S. homes amounts to about 150 billion kilowatt-hours (16% of total residential electricity use) at a cost of $11 billion and is responsible for emissions of more than 100 million tons of carbon dioxide, the primary “greenhouse gas.” We can significantly reduce these numbers through the use of more efficient residential light sources. The compact fluorescent lamp (CFL) is the most dramatic example of such a technology. Unfortunately, the actual *applications* of CFLs have often failed to deliver on the promise of equivalent light quality, quantity, and distribution.

Two cutting-edge regulatory issues in the energy-efficiency arena today are the verifiability and persistence of energy savings claimed for utility conservation programs. As regulatory scrutiny of utility demand side management (DSM) activities has become more sophisticated, it is no longer acceptable to rely on simple “back of the envelope” engineering assumptions and calculations of energy savings to justify spending on conservation programs. Such calculations can gloss over critical characteristics of technology performance in the field and lead to unacceptable disparities between estimated and actual energy savings and cost effectiveness. It is critical that proponents of energy efficiency design their programs with sufficient integrity to resist such critiques. Utilities become increasingly impacted by these issues when their profit incentives for energy savings are shifted (via regulatory directives) from estimated to actual performance.

Durable energy savings from CFLs can only be achieved when lamp, ballast, and fixture are treated as a unified whole—as a system. The temptation to simply replace incandescent sources with “screw-in” CFLs, without considering the entire luminaire, often results in unanticipated losses in light output, severe degradation of optical distribution, and visual discomfort caused by glare. In many cases, permanently “dedicated” CFL luminaires—with lamp, ballast, and fixture holistically optimized—are viable substitutes for incandescent systems. In addition to energy savings, the development of dedicated CFL fixtures represents one of the largest new business and market opportunities for both the lamp and fixture industries.

It is with the aforementioned issues in mind that we are working to unite the diverse stakeholders within the lighting industry, to work with utilities and government agencies, and to develop consumer information to further the acceptance and penetration of the CFL fixture into the residential market.

FINDING THE TARGET

Market Status

With U.S. sales approaching 30 million CFLs per year (and 200 million globally), compact fluorescent systems are seeing increased application in *commercial* interiors. In striking contrast to trends in the commercial sector, most efforts to accelerate the penetration of CFLs in the residential market have been limited to utility rebate programs for screw-base compact fluorescent technology. Little attention has been paid to fixtures.

About three billion light fixtures illuminate America’s 96 million homes (4 out of 5 of these are incandescent and the rest are fluorescent) (Sardinsky 1995). Each year, an estimated 500+ domestic and foreign manufacturers collectively sell about 165 million residential fixtures with a retail value of over four billion dollars. Of this total, roughly 70% of all fixture sales are for new construction and 30% are for improvement/renovation. Of all fixtures sold (both domestic and imported), approximately 60% are hardwired and 40% are portable. Of hardwired fixtures, about 60% are sold for new residential construction, compared to only about 25% of total portable fixture sales.

Half of all fixtures sold in the U.S. are imported (and sold at one-third lower price on average), as indicated in Figure 1, with imports accounting for one-third of all hardwire fixtures and two-thirds of all portable fixtures.

Figure 1. Residential hardwire and portable lighting fixture sales in the U.S.–1993 (includes domestic, import, and export shipments) (Sardinsky 1995)

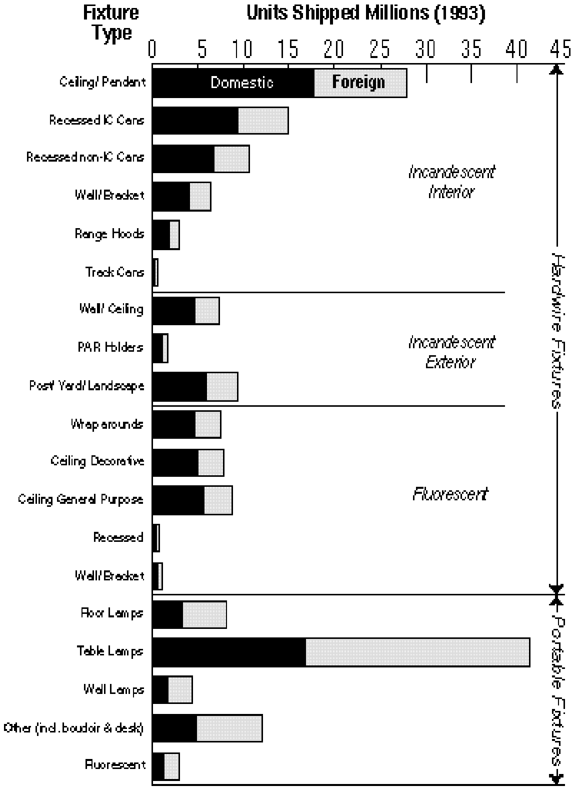
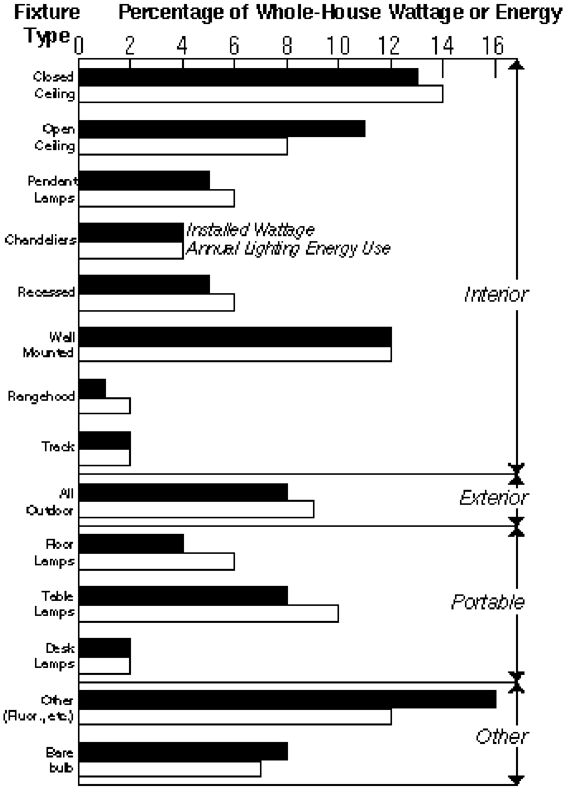


Figure 2. Tacoma Public Utilities survey comparison if installed wattage and annual lighting energy use (based on two six-month light-logger studies among 81 homes)

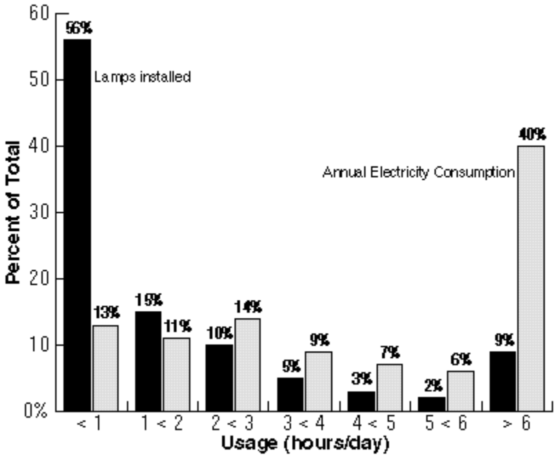


Energy Use

A new long-term monitoring study being conducted by the Tacoma Public Utilities (six utility companies located in the Pacific Northwest) and funded by the Bonneville Power Administration is generating residential lighting end-use information far more detailed than anything previously available. Light loggers are being rotated among 200 homes over a two-year period in order to quantify information such as the amount of lighting energy use by fixture type. The preliminary results shown in Figure 2 reflect the data collected during the first year of this study (personal communication, David Lerman, TPU). Ceiling-mounted fixtures and table lamps emerge as among the most important fixture types. This is significant, given that these are among the most difficult in which to effectively implement compact fluorescent lamps. Moreover, as seen in Figure 1, about 27 million ceiling-mounted fixtures and 40 million table lamps were sold in the U.S. in 1993.

The survey data also show that 75% of residential lighting energy is consumed by just 30% of a typical home's fixtures, i.e. "high-use" sockets (Figure 3). These sockets, which include surface-mounted fixtures common to living rooms, kitchens and bathrooms; and table and floor fixtures in living rooms; and exterior/outdoor fixtures, make good first targets for replacement or conversion to CFLs. Successfully converting that 30% of sockets to CFLs would reduce the U.S. annual usage by 85 billion kilowatt-hours annually, worth 6 billion dollars in utility bills, and eliminating the need for roughly 68 new 250-megawatt power plants.

Figure 3. Distribution of installed lamps and energy use by burning hours (TPU Survey)



CONSERVATION POTENTIAL IS DEPENDENT ON TECHNOLOGY CHOICES

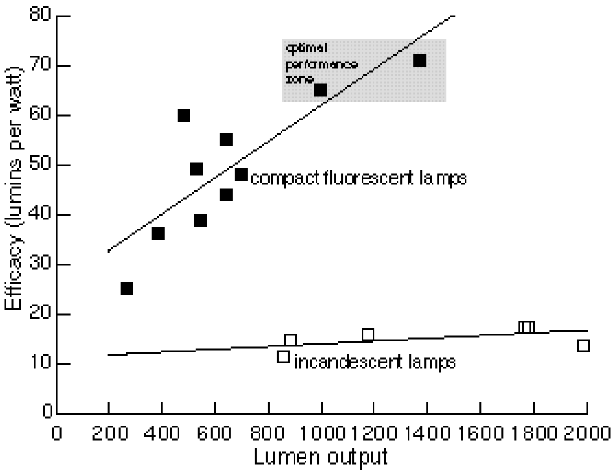
Screw-Base Retrofit Systems

Specific CFL technologies can have dramatically different technical and economic performance characteristics. When improperly applied, CFLs will not achieve their nominal performance rating and thus will fail to provide energy services (light output and quality) equivalent to those of the incandescent lamps they replace.

Screw-base retrofit systems typically include a lamp, a ballast, and a threaded “Edison” base for interfacing with existing incandescent sockets and fixtures. The lamp may be integral with the ballast or it may be removable for re-lamping. Problems with screw-base CFLs are documented in a survey by the Electric Power Research Institute (EPRI 1992). The fundamental barrier to screw-base CFL technology as a long-term solution is the so-called “snapback” effect: when these units burn out—or even before that time—they can be replaced with inexpensive incandescent lamps, thereby eroding their conservation potential.

Our laboratory measurements taken inside a photometric integrating sphere show that significant losses in efficacy can occur as a function of operating conditions encountered within the fixture environment. Figure 4 shows our measurements of variations in efficacy for a range of CFL screw-base systems (a range of incandescent sources are included for comparison). Optimal efficacy was achieved with bare, electronically ballasted lamps operating base-up. As indicated in the graph, significant losses in lumen output can occur, mainly from lumen losses experienced as a function of ambient temperature, burning position, ballast losses, and optical factors.

Figure 4. Variations in efficacies for CFL and incandescent light sources



As the ambient air temperature around a fluorescent lamp rises above or falls below 77°F (25°C)—the optimal temperature upon which nominal “advertised” product performance is based—its lumen output steadily decreases below its rated value. This thermal effect is particularly important in the case of CFLs in enclosed fixtures. The hotter environment obtained in small fixtures causes the lumen output of the CFL to drop to 80% or less of its rated value, which already tends to be low compared to an equivalent sized incandescent lamp for the other reasons indicated above (Siminovitch et al. 1990; NLPIP 1993). Unlike linear fluorescent systems, CFL power usage does not decline along with light output. As a result, efficacy (lumens per watt) drops dramatically as the optimal operating temperature is exceeded.

Most existing residential fixtures have been designed for the operation of incandescent A-lamps, which have a very different luminous distribution from the more linear and asymmetrical CFL and are not sensitive to temperature. Replacing an incandescent A-lamp with a screw-base compact fluorescent will change the optical distribution of the existing fixture (NLPIP 1993), potentially reducing perceived brightness, adding to consumer dissatisfaction. Furthermore, operating a variety of sizes (wattages) of A-lamps in a given fixture will not result in significant *relative* variations in candlepower distribution, whereas consumer choices of size and type of screw-base CFL will lead to dramatic variations.

The problems with screw-in CFLs have assumed more than an academic interest. Many utilities have “derated” assumptions about the performance of CFLs to reflect the gap between ideal and actual operation. Southern California Edison, for example, assumes that screw-base lamps are in service for 6 300 hours rather than the 10 000-hour life with which the lamps are typically labeled. Throughout the Pacific Northwest area, utilities assume a 7 000 hour service life. This shorter life reflects expectations about realities such as premature reversion to incandescents, lamps obtained by consumers but never installed, and reduced operating life due to adverse conditions in the fixture. The Sacramento Municipal Utility District assumes that 10% of all CFLs are removed prematurely from their sockets; the Los Angeles Department of Water and Power assumes found that 45% had been removed within two years. Such adjustments have a considerable negative effect on cost-effectiveness. From the utility’s perspective, this means that rebates and other promotion efforts are less often justified.

Dedicated Fixtures Using Pin-base Compact Fluorescent Lamps

In contrast to the screw-base approach, dedicated luminaires include a fixture whose elements are electrical connections, ballasting, optical control, and aesthetic integration of lamp and reflector. A specified, separate replaceable pin-base lamp can be positioned appropriately to maximize optical distribution and maintain an optimum thermal environment. The pin-base lamp interfaces with a socket in the fixture, as is typical of commercial fixtures.

In dedicated luminaires, fixture geometry and thermal performance, the most important optimizing factors, can be managed to maximize light output and optical distribution of the compact fluorescent, thereby maintaining high fixture efficiency. In addition to better performance, the biggest advantage over a screw-base system is that when the lamps burn out a dedicated fixture can be re-lamped only with pin-base CFLs, eliminating the snapback effect.

From a lifecycle perspective, a pin-base compact fluorescent lamp is significantly less expensive than the more complicated screw-base system, and it can thus be inventoried at home more economically (and more compactly). With dedicated fixtures, less solid waste is produced upon disposal, and mercury recovery is significantly (about 50%) less expensive than with screw-base integral units (Mills and Borg 1993). Other advantages of pin-base systems include greater ability to address power quality issues in the ballast and easier implementation of dimmable ballasts.

Gonio-Photometric Analysis for Residential CFL Optimization

We designed, constructed, and calibrated an experimental apparatus and conducted a series of goniophotometric candela distribution studies on a broad range of residential fixtures, including table lamps and ceiling-mounted fixtures originally designed for A-lamps.

The first series of tests focused on the distribution characteristics of various light sources in a standard table lamp as shown in Figure 5. The candlepower distribution plots in Figures 5a show the light intensity at all angles around a table lamp operating without the shade and using a 100W incandescent A-lamp, a nominal 23W triple tube CFL, and a 22W Circline fluorescent lamp (measured wattages 103.2W, 19.0W and 22.8W respectively—reflecting ballast factors typical of products in the U.S. market). The donut-shaped T12 Circline lamp is a very common—and relatively inexpensive—style of CFL in the U.S. market. The plots show the results of one continuous sensor sweep around the lamp and map out the candlepower distribution in a single vertical plane. Nadir is shown as 0° on the plot and corresponds to readings directly under the lamp, while zenith occurs at 180° and represents readings directly above the fixture. These figures illustrate how different light sources can yield widely varied light distributions.

Figure 5a shows the fairly symmetric intensity distribution of the 100 W A-lamp in comparison to two types of CFL. The intensity varies between 100 and 170 candelas, except for where the fixture base blocks the flux at near-nadir angles of <20°. The triple lamp (“T-lamp”) is most intense (with over 130 candelas) at 90° because of its predominately vertical illuminating surfaces. The intensity drops to less than 40 candelas near zenith angles because the lamp’s projected area is relatively small there. Again, the intensity diminishes near nadir until the fixture’s base is again encountered, blocking all flux. The Circline lamp distributes the majority of its flux vertically due to a predominance of horizontal illuminating surfaces. Its intensity ranges from more than 190 candelas at zenith to a minimum of 90 candelas at 90°. Additionally, since the lamp extends out beyond the fixture base, over 90 candelas are found at nadir.

A comparison of the A-lamp and the Circline lamp demonstrates the advantages of directing light output vertically. While the A-lamp yields the largest total lumen package of 1815 lumens, the Circline has a much more intense output at the crucial nadir and zenith angles. In effect, fewer total lumens are required to produce sufficient illumination where it is actually needed: at nadir for task lighting and zenith for indirect lighting.

Figure 5 shows how these light distributions are affected by the addition of a white, fluted lamp shade to the table lamp. In all cases, the shade blocks flux in the 50°-140° range and redirects it into the 0°-50° and 140°-180° zones. This has the effect of blocking potential glare and redirecting flux to areas where it can be used for indirect (140°-180°) or task (0°-50°) lighting. Since shade absorption is inversely proportional to fixture efficiency, we would expect that the more flux a lamp sends into the shade zone, the less total flux leaves the fixture. Our results indicate that the triple lamp transmits the most flux (82.6%) into the shade zone, followed by the A-lamp (77.1%), and then the Circline lamp (64.1%). Consequently, the Circline lamp retains 87.2% of its total light output when the shade is added, while the A-lamp drops to 83.4%, and the triple lamp falls to 81.9%.

A second series of goniometric tests were conducted using two nominal 60W A-lamps, two 13W CFLs and a 22W Circline in a standard enclosed 10-inch (25 cm) diameter ceiling-mounted fixture (measured wattages 121.2W, 24.2W and 23.5W respectively) at seen in Figure 6. The white translucent diffuser acts to limit glare. It also has the effect of offsetting the differences in the shapes of the candlepower plots yielding similar shaped plots for all three sources (although scaled according to their total light output). The A-lamp fixture has an efficacy of less than 9 LPW. As with the table lamp, the A-lamp suffers fixture losses by sending light symmetrically instead of focusing flux vertically where it can exit the fixture. The CFLpackage gives more than a 4-fold increase in efficacy. However, the Circline fixture is significantly dimmer than the other fixtures and barely doubles the efficacy of the A-lamp fixture, a disappointing result for an incandescent to fluorescent conversion. The fixture efficacy results are summarized in Figures 7a-b.

Figures 5-6. Goniometric test results for table lamps and ceiling-mounted fixtures operating with CFLs and incandescent lamps (with and without shade and diffuser in place)

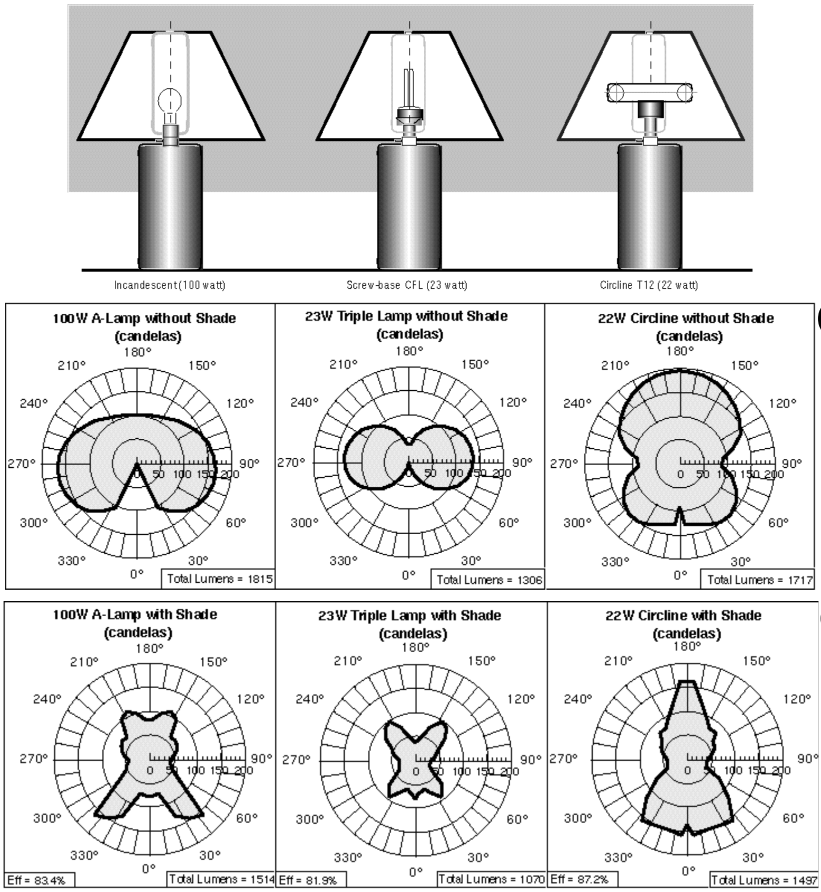


Figure 5.

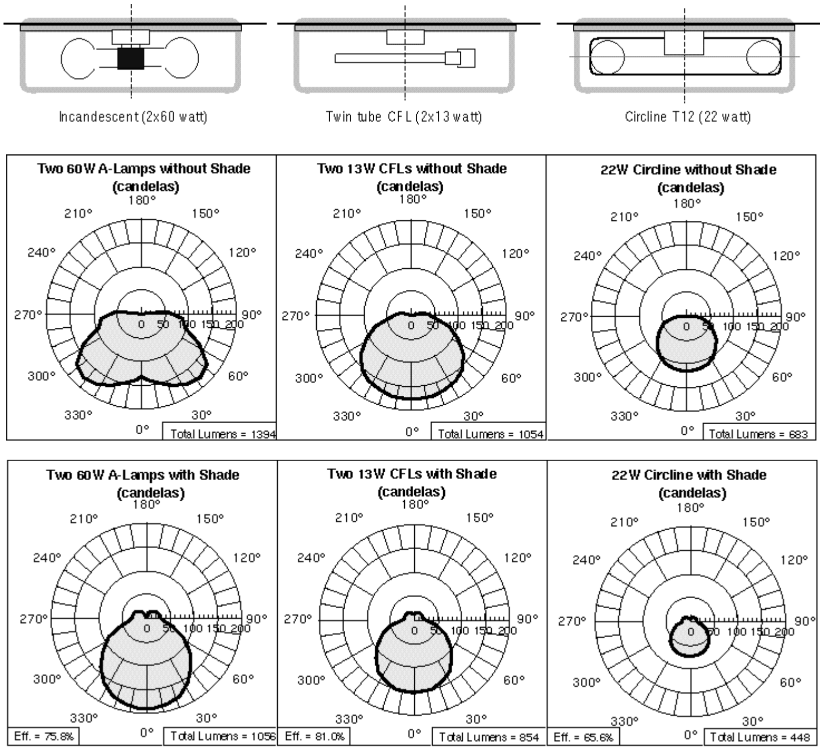


Figure 6.

Figure 8 (below). Candela plots standard vs. optimized Circline lamp

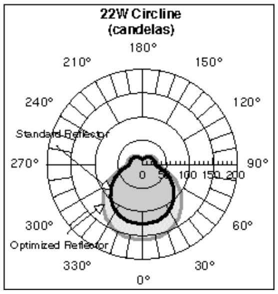
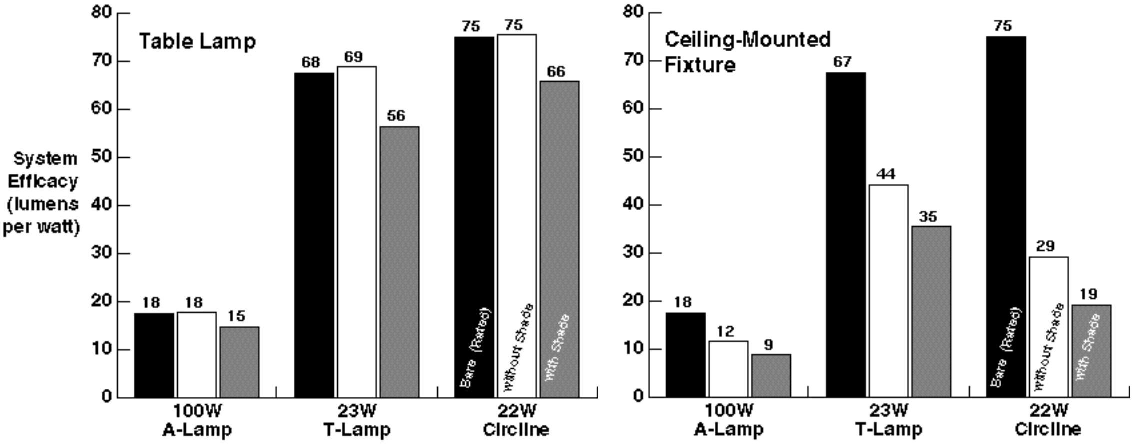


Figure 7a-b. Efficacies for photometric fixture case studies shown in Figures 5 and 6 (nominal, rated efficacies shown for comparison)



The poor performance of the Circline fixture is mainly due to the source/fixture size ratio. By placing a large source in a small fixture, much of the light is reabsorbed by the source, rather than exiting the fixture. The addition of the diffuser acts to increase the internal fixture reflections, compounding the Circlines fixture losses. The inclusion of a black ballast inside the Circline fixture, as currently sold, only compounds this fixture’s internal absorption problems. Tests show that optimizing the internal reflectance of the ballast can results in nearly a 20% increase in the efficacy (Figure 8, page 6).

The CFL fixture with the relatively small twin tube CFL sources only experiences a 20% loss in efficacy with the addition of the diffuser (as compared to 24% for the A-lamp and 34% for the Circline). This horizontal CFL fixture achieves the highest fixture efficiency by both having a favorable source/fixture size ratio and by focusing its light vertically.

In summary, goniometric studies show that significant differences in light distribution can occur when CFLs are installed into fixtures originally designed for A-lamps. Lamp position and geometry can have a significant effect on the light output, light distribution, and fixture efficiencies. The data suggest that a predominately horizontally oriented source (in this case a Circline) outperforms both a symmetric (A-lamp) and a predominately vertically oriented source (triple lamp) in table lamp fixtures. Thus, the Circline lamp proves to be more efficient than the A-lamp not only because of the inherent advantage in fluorescent vs. incandescent lighting, but also because of its distributional characteristics. Small CFL sources that direct flux vertically were found to outperform both A-lamps and Circline sources in ceiling-mounted fixtures. Our ongoing studies with the fixture manufacturing industry continue to develop new fixture designs that optimize the focused distributions of CFLs. These studies suggest two important findings: 1) the ideal source for a fixture is dependent on the fixture’s geometry and the application of the luminaire, and 2) dedicated fixtures that are engineered for the flux of the CFLrather than the typical A-lamp, have the possibility of dramatically increasing fixture efficiency and light output.

MARKET TRANSFORMATION:
MOVING FROM INCANDESCENT TO CFL FIXTURES FOR THE HOME

The future mix of lamp types in the home will be based on a range of sources including incandescents, tungsten halogens, and compact and linear fluorescents. Incandescents will remain in most of the sockets due to the predominance of low-burning-hour sockets and economics. Rather than attempting to convert an entire household to CFLs, a market transformation program should target heavy-use fixtures first, as they represent a small subset of the total applications and have a disproportionately large large overall savings potential. As noted previously, replacing the 30% high-use fixtures with high-performance dedicated CFLfixtures would achieve more than 50% savings in lighting energy for the home.

We estimate that over 1 billion of the existing fixtures—and 100 000 of new sales each year—are candidates for cost-effective CFL upgrades. However, the complexity of the marketplace requires a variety of strategies. Fixtures tend to find their way into the home through a variety of different specification and distribution channels. Consumers procure the majority of hardwired fixtures for new construction through their builders and electrical contractors and for renovation/replacement through lighting showrooms and do-it-yourself retailers. The majority of portables are procured through lighting showrooms, discount stores/mass merchandisers, and department stores. All told, there are at least 150 000 wholesale and retail sales outlets for these fixtures. Among these, there are 39 000 furniture/home decor stores, 29 000 hardware stores, 31 000 department stores, 8 000 electrical equipment distributors, and 4 800 lighting showrooms.

The fixture manufacturing industry is relatively concentrated, with 70% of the market shared by 50 (out of 500+) companies. The fact that half of all residential light fixtures sold in the U.S. are imported adds a complicating dimension to the problem of designing programs to promote increased energy efficiency. At the same time, it provides a market incentive for U.S. manufacturers to establish themselves in the forefront of energy-efficient fixture manufacturing.

Developing and accelerating the application of dedicated CFL fixtures for the home is a worthy but elusive goal. Part of the difficulty stems from the fragmentation among the variety of “stakeholder” groups that could potentially work together—lamp manufacturers, fixture manufacturers, ballast manufacturers, wholesalers, retailers, home builders, third-party buyers, lighting designers and specifiers, governments, utilities, and consumers. Another obstacle is the lack of sufficient information. Among the most formidable barriers is the reluctance of manufacturers to develop new product lines and of consumers to pay the cost premium for efficiency. The elements of a balanced national program are described in more detail by Siminovitch and Mills (1995), and are summarized below.

- Fostering Cooperation between Industry and Government Energy Research and Policy Bodies (R&D towards commercialization of better products and a wider variety of efficient applications)

- Creating Better Market Information (market research and statistics, product labeling, energy end-use data)

- Financial Incentives and Market Pull (manufacturer and consumer rebates, design competition, marshalling the buying power of large purchasers)

- Professional Education and Demonstration (for all “stakeholder” groups listed above)

- Governmental Leadership (provision of independent information, developing voluntary and mandatory building codes, product efficiency standards, and use of purchasing power for government-owned or subsidized housing)

Progress has been made on each of these fronts, but past efforts have been fragmented, with insufficient coordination among the concerned parties. Government-sponsored research and development is underway in the DOE national laboratory system and the EPA Pollution Prevention programs are well-positioned to stimulate manufacturers and consumers of efficient lighting products. Information on selected lighting products is gathered and published by the National Lighting Product Information Program, carried out by the Lighting Research Center (NLPIP 1993). Standards on lighting components and whole-building lighting power densities have been developed for non-residential buildings (and for linear fluorescents in kitchens and bathrooms in some states) but little effort has otherwise been spent on the residential sector. The Energy-Efficient Collaborative and Product Network” is a new effort among government agencies to direct government purchasing towards efficient products, including residential lighting.

CONCLUSION

With few exceptions, current efforts to accelerate residential use of compact fluorescent systems have been focused on rebate programs for screw-base CFL systems. While such systems represent a simple approach to replacing incandescent lamps, they are a short-term solution, with several inherent technical, economic, and aesthetic integration problems that severely limit the persistence of long-term energy conservation in the home. Dedicated fixtures using pin-base compact fluorescent lamps have the potential to successfully address those problems, although the current market is underdeveloped. Because dedicated fixtures can be designed for the optimum performance and aesthetics of compact fluorescent lamps, they will be able to significantly improve consumer confidence in the new technology and in energy efficiency in general.

ACKNOWLEDGMENTS

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